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Minimizing Detector Response in Neutron Multiplicity Measurements

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Outline

- Introduction/Motivation
- Theory
- Methods – Measured and Simulated
- Results
- Conclusions

Introduction

- **Neutron multiplicity measurements usually are accompanied by simulations**
  - Comparisons inform on the accuracy of the simulation model
- **Both experiments and simulation have sources of error and uncertainty**
  - Positions of detectors and other objects
    - Affects efficiency, and therefore count rates
  - Detector response can be complex to depict appropriately
- **A parameter that minimizes reliance on detector response would allow for more direct comparison between a measurement of a source and its respective simulation**

Introduction (cont.)

- Manipulation of Hage-Cifarelli formalism [1] creates a detector independent parameter
- Lower fidelity simulations performed at Los Alamos National Laboratory have previously shown that such a parameter (termed Sm_2) does behave independent of detector efficiency [2]
- Need for testing with experimental data and more detailed simulations

Theory

- **From Hage-Cifarelli formalism:**
  - $R_1 = \varepsilon M_L \overline{\nu_{S1}} F_s$
  - $R_2 = \varepsilon^2 M_L^2 \left(\overline{\nu_{S2}} + \frac{M_L - 1}{\overline{\nu_{I1}} - 1} \overline{\nu_{S1}\nu_{I2}} \right) F_s$
- **Both depend on the properties of the nuclear material and detector response**
- **Eliminate ε by taking the ratio**

$$Sm_2 = \frac{R_2}{R_1^2} = \frac{\overline{\nu_{S2}} + \frac{M_L - 1}{\overline{\nu_{I1}} - 1} \overline{\nu_{S1}\nu_{I2}}}{\overline{\nu_{S1}}^2 F_s}$$

- **Sm_2 therefore does not depend on detector response**
  - Should be independent of factors like solid angle, and therefore detector separation distance

M_L = Leakage multiplication
F_s = Spontaneous fission rate
$\overline{\nu_{S/In}}$ = nth reduced moment of induced/spontaneous fission neutron multiplicity distribution
ε = Total efficiency

Theory (cont.)

- **From standard error propagation**

$$\sigma_{Sm_2} = Sm_2\sqrt{4\left(\frac{\sigma_{R_1}}{R_1}\right)^2 + \left(\frac{\sigma_{R_2}}{R_2}\right)^2}$$

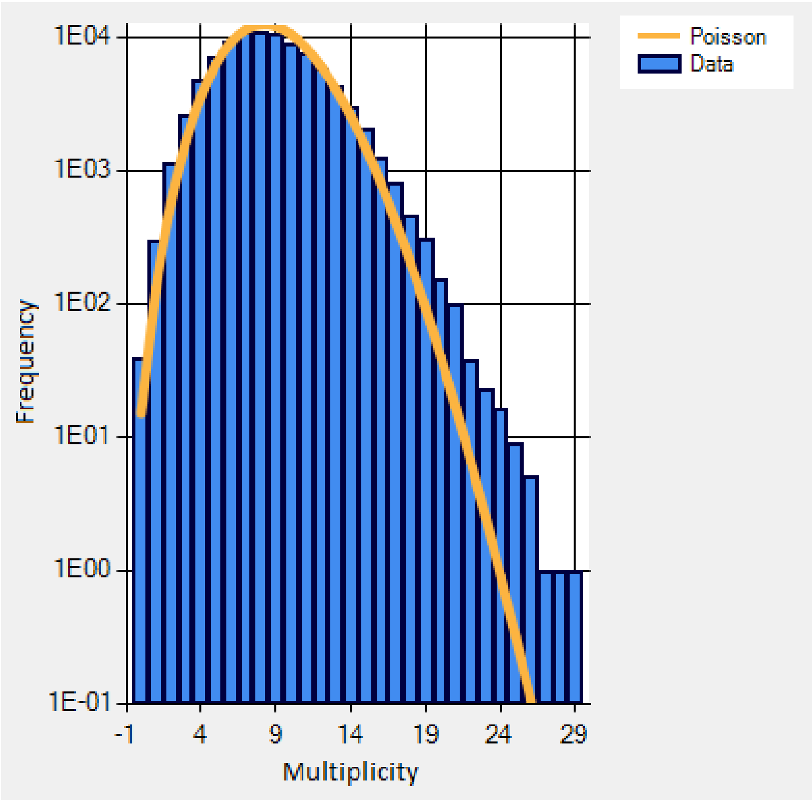
  - Uncertainty in ratio dependent on uncertainties in count rates

- **Other possible ratios (e.g. . R_3/R_2R_1 and R_3/R_1^3)**
  - Inclusion of triples rate leads to worse statistics, more complicated math

Method – Measured Data

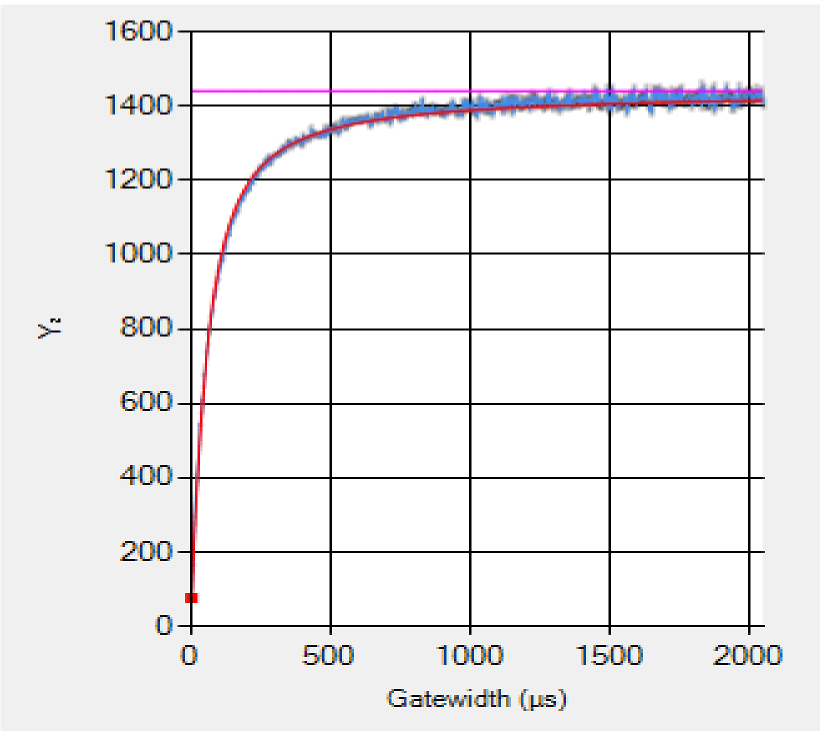
- **Five-minute measurements performed with 4.5 kg sphere of α-phase plutonium [3-6]**
  - “BeRP ball”
  - ~6% ^{240}Pu
- **Detector was the LANL NoMAD**
  - Series of ^{3}He tubes in high-density polyethylene matrix
- **Ten cases measured between 30-77.5 cm**

Method – Measured Data (cont.)



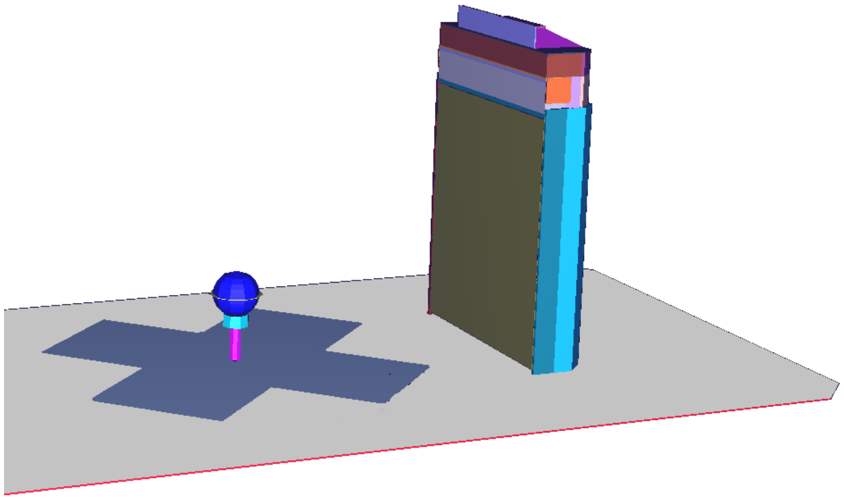
- **NoMAD outputs list of interactions**
  - Which tube interaction happened in and at what time
- **Processed with Momentum [7]**
  - Implements random time binning [8] to create Feynman histograms
  - Calculates Rossi-α distribution

Method – Measured Data (cont.)



- **Momentum uses histogram moments to produce count rates**
  - R_1, R_2
  - Uncertainties based on covariance matrix
- **Additionally, computes parameters such as multiplication and Feynman-Y**

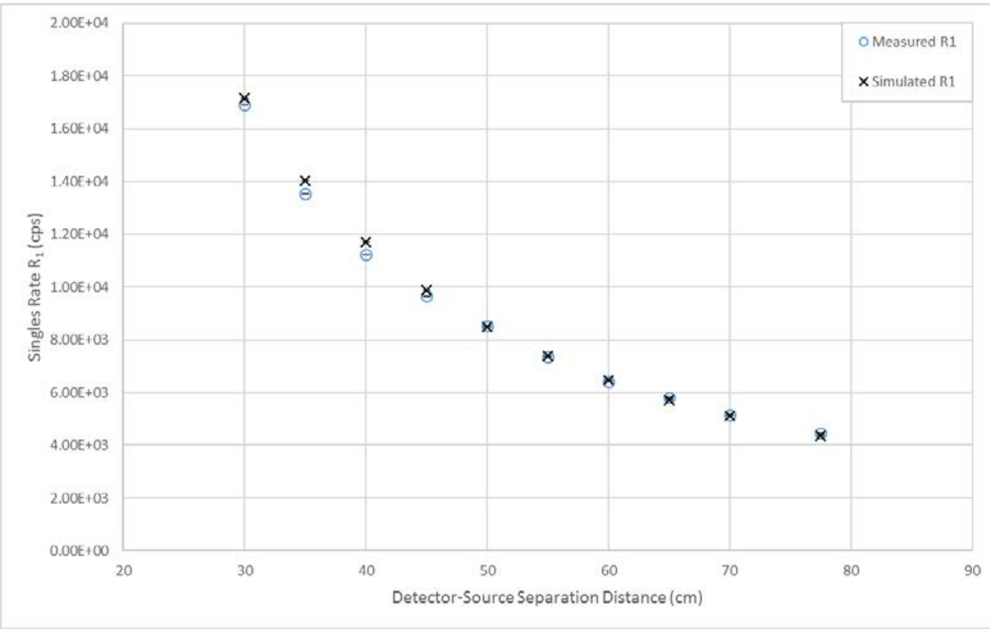
Method – Simulated Data



Graphic made with MCNP Visual Editor [10]

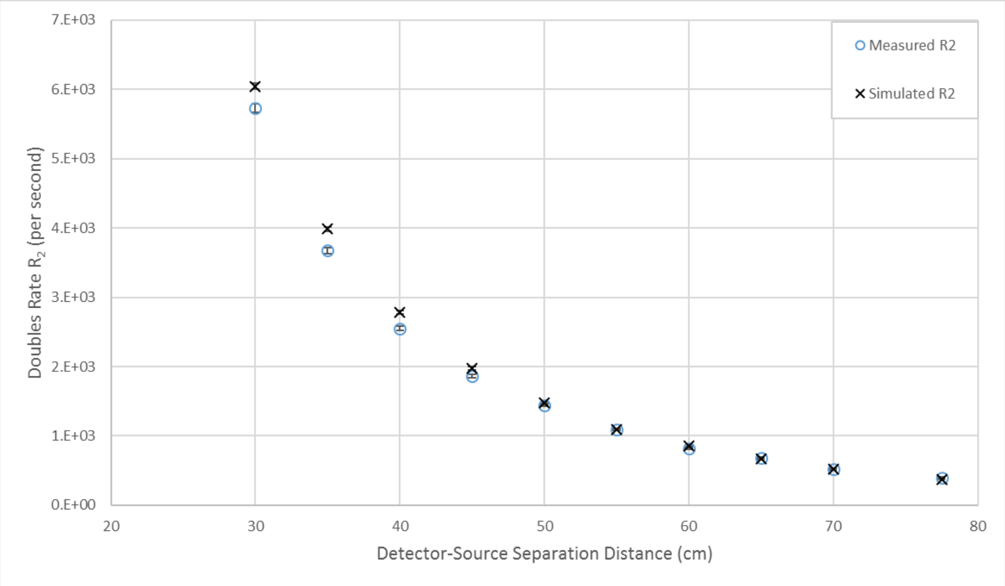
- **Simulations performed with MCNP® version 6.1.1 [9], ENDF/B-VII.1 cross sections**
- **Replicates the five-minute measurement**
- **MCNP Ptrac file manipulated with mcnptools to mimic NoMAD output**
    - Accounts for dead time
    - Processed in the same fashion

Results – Singles Rates



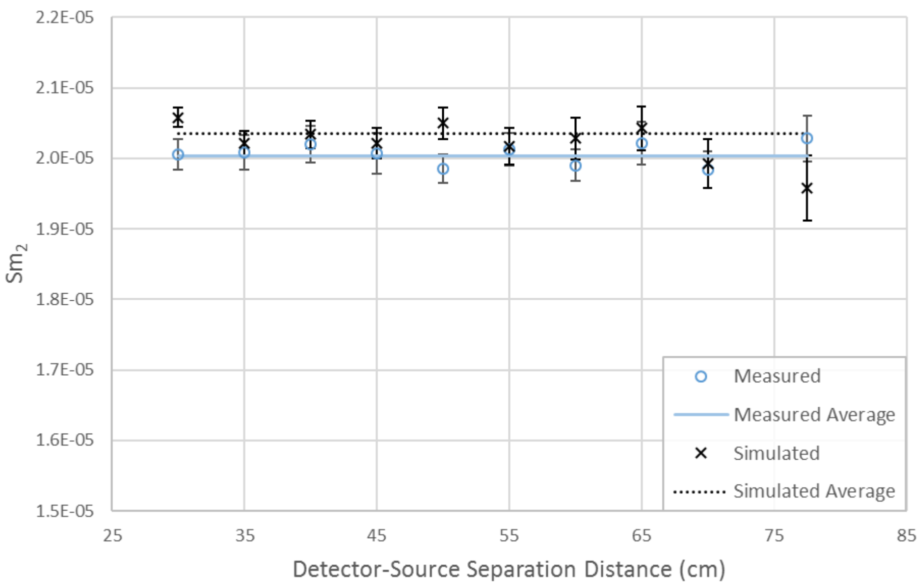
- **If looking at the singles rate, no consistent trend**
  - Some simulations overestimate by as much as 4%
  - Some underestimate by almost 2%

Results – Doubles Rates



- **This continues with the doubles rate R2**
  - Some simulations overestimate, some underestimate

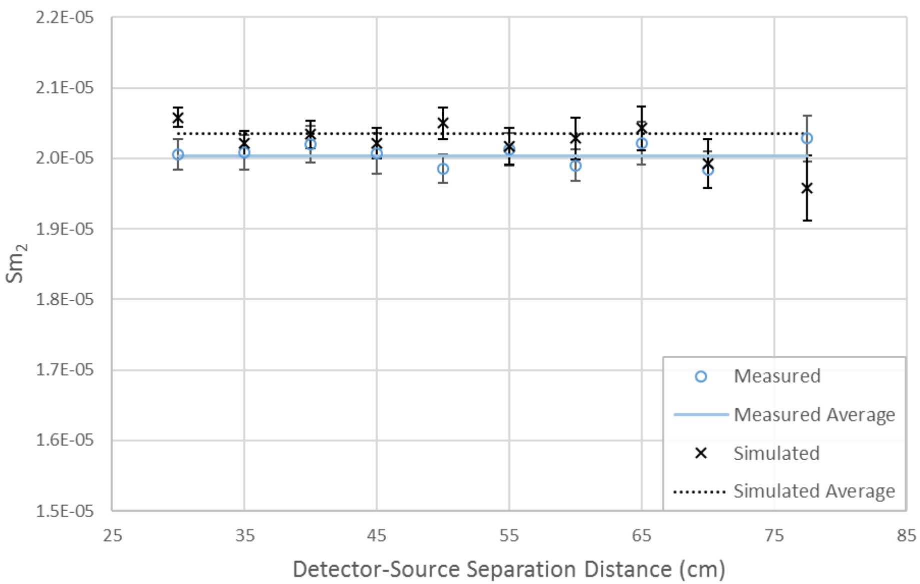
Results – Sm_2



- **More consistent trend**
  - Most simulations overestimate
- **Can use the overestimations to make more informed changes to model**
  - From Sm2 equation, overestimation could be due to low spontaneous fission rate or high multiplication

$$Sm_2 = \frac{\overline{\nu_{S2}} + \frac{M_L - 1}{\overline{\nu_{I1}} - 1}\overline{\nu_{S1}\nu_{I2}}}{\overline{\nu_{S1}}^2 F_s}$$

Results – Sm_2 (cont.)



- **Both simulated and measured data fit to a flat line**
  - Shows independence from detector efficiency as expected
- **Simulation results relatively close to their measured counterparts**
  - Within 5.5%
  - Weighted averages within 2%

Conclusions

- **Sm_2 minimizes detector response**
  - Mostly depends on the nuclear material and any reflecting components
- **Parameter should allow for much more direct comparison between simulations and experiments involving nuclear material**
  - Sm_2 indicates accuracy of model, not accuracy of detector positions or other detector parameters
- **Models of experiment can be less detailed due to omission or simplification of detector**
  - Only need a way to produce the count rate moments

Limitations and Assumptions

- **Hage-Cifarelli formalism uses some assumptions**
  - Insignificant detector dead time, induced fissions occur at the same time as emission of their inducing neutron, point sources, etc.
- **Equations shown for count rates, Sm_2, assume (α, n) emission negligible**
  - Shouldn't affect outcome, just the equations
- **Any reflectors used in detectors may have an effect (however small) on Sm_2 value**

Future Work

- **Re-derive Sm_2 equation using original Hage-Cifarelli expressions that include (α, n) emission**
- **Push detector independence to the limit**
  - Test other types of detectors, run simulations with no detectors
    - Have tested detector-less models with MCNP, working on PARTISN simulations
- **Explore relationship between reflecting materials and Sm_2**

References

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- 2. M. A. SMITH-NELSON, J.D. HUTCHINSON, "The Sm2 Ratio for Evaluating Neutron Multiplicity Models." LA-UR-14-29047, Los Alamos National Laboratory, (2014).
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- 7. M. SMITH-NELSON, "Momentum: version 0.36.3," LANL Software, March 29, 2015.
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- 9. J.T. GOORLEY et. al., "Initial MCNP6 Release Overview," Nuclear Technology, 180, 298-315 (2012).
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Thanks!

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Verifying Uncertainty Formula

- **Simulated large numbers of “experiments” by creating random count rate data**
  - Assumed Gaussian distribution for count rates
  - Computed and Sm_2 value for each set of random rates

- **Two tests for computed standard deviation:**
  - Chebyshev Inequality
    - Minimum percentage of values must be within x standard deviations of the mean
    - 75% within two σ
    - 50% within $\sqrt{2}\ \sigma$
  - Computed $\sigma = \sqrt{E[x^2] + E[x]^2}$ for the set of Sm_2 values, compared to formula

Verifying Uncertainty, cont.

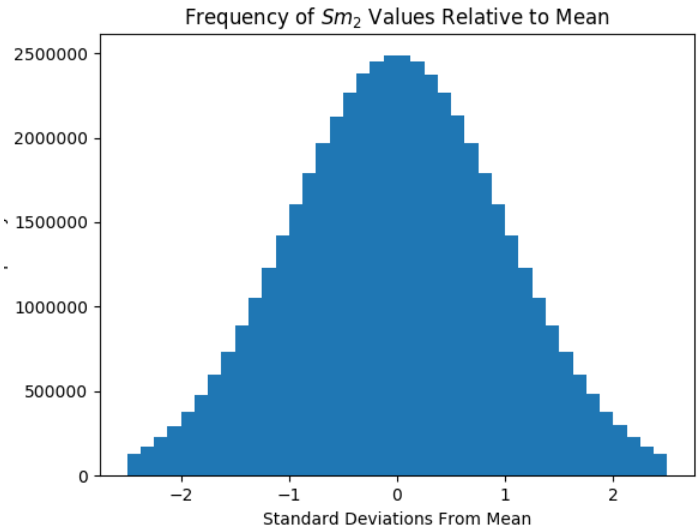
- **Three BeRP Ball Cases:**
  - NoMAD 30cm away
    - High R_1, R_2
  - NoMAD 77.5 cm away
    - Low R_1, R_2
  - “Barebones” simulation model
    - Just tracking particles leaving ball
    - Very High R_1, R_2
- **One Cf-252 Measurement**
  - NoMAD 80.2 cm away
    - Low R_1, Lower R_2
- **50 million trials**

Case	R_1	R_2
BeRP 30 cm	1.687×10^4	5.726×10^3
BeRP 77.5 cm	4.458×10^3	4.030×10^2
“Barebones” Simulation	8.438×10^5	1.419×10^7
Cf-252 80.2 cm	1.564×10^3	1.188×10^1

Verifying Uncertainty, cont.

- **All cases have great agreement between theoretical and experimental σ_{Sm_2}**
  - <<1% difference
- **Chebyshev inequality also passed with flying colors**
  - ~95% within two σ
    - Follows usual behavior of normal distributions
  - >84% within $\sqrt{2}\,\sigma$

Case	Difference in σ_{Sm_2}
BeRP 30 cm	-0.02%
BeRP 77.5 cm	0.005%
“Barebones” Simulation	0.007%
Cf-252 80.2 cm	0.02%



Computing Leakage Multiplication

- **Given an Sm_2 value, it is possible to solve for M_L if spontaneous fission rate and multiplicity distribution is known**

$$M_L = 1 + \frac{(\overline{\nu_{I1}} - 1)\left(Sm_2 \overline{\nu_{S1}}^2 F_S - \overline{\nu_{S2}}\right)}{\overline{\nu_{S1}\nu_{I2}}}$$

- **Used simulation F_s for both measured and simulated data**

- **Average of cases gives 3.646 for measurements, 3.671 for simulations**
  - 0.69% difference
- **Using Momentum, averages for leakage multiplication become 3.438 for measured, 3.463 for simulated**
  - 0.74% difference